Tracking, pulsed ultrasonic interferometer

William T. Angel and Vern E. Bean

National Bureau of Standards, Washington, DC 20234

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A pulsed ultrasonic interferometer was designed and constructed that has the ability to track changes in transit time as the ambient pressure and temperature of the sample are changed. The stability over 17 h approached one part in 10^7. This instrumentation will be incorporated into an automated high pressure transfer standard calibration system.

Ultrasonic interferometry is frequently used to determine the pressure and temperature dependence of the speed of sound or the characteristic transit time of the sound wave in solids or liquids. Once these dependencies are known, it is possible to determine ambient pressure and temperature of a sample from the transit time measurements. In this type of measurement, one normally measures a frequency which is proportional to the reciprocal of the characteristic transit time. The temperature (T) and pressure (P) coefficients of the frequency (f) are defined by

$$C_T=\frac{1}{f}\frac{\partial f}{\partial T} \quad \text{and} \quad C_P=\frac{1}{f}\frac{\partial f}{\partial P}.$$

For a shear wave in fused quartz, the temperature coefficient is about -8×10^{-5} K^{-1}, and the pressure coefficient is about 6×10^{-11} Pa^{-1}.[1] Using fused quartz as the sensor, the determination of temperature with a precision of 1 mK requires the measurement of frequency of about 8 parts in 10^8. Similarly, the determination of pressure with a precision of 10^4 Pa requires the measurement of frequency to within 6 parts in 10^7.

Before using any material as an ultrasonic pressure or temperature gauge, one must be certain that the transit times of such materials are indeed stable to the levels indicated, and the possible aftereffects of pressure or temperature cycles must be investigated for long periods of time. In the pursuit of such measurements, we have developed an automatic pulsed ultrasonic interferometer which has a stability approaching 1 part in 10^7. Similar instrumentation systems have been previously developed,[2] but none that are completely automated appear to realize the baseline stability for time intervals of several hours that is a primary requirement for this application. We shall first consider the interferometer in its simplest form and then describe its automation.

A block diagram of the basic interferometer is shown in Fig. 1. The output of the continuous wave oscillator is gated by the rf switch to provide rf pulses which are then amplified, routed to the sample via the circulator, multiply reflected, and returned to the circulator. The output of the circulator is a train of echoes which is again amplified and then phase sensitive detected in the mixer using the original continuous wave from the oscillator as the reference. The output of the mixer is a series of dc pulses, one pulse for each echo, with amplitudes proportional to the phase differences between the reference and the rf within the echoes. Displaying the output of the mixer on an oscilloscope, one selects the echo to be used and then critically adjusts the frequency of the oscillator until the signal from the chosen echo is zero. If the system is adjusted so as to achieve the above at a frequency close to the resonance frequency f_r of the transducer, then the phase angle at reflection will remain essentially constant,[3] and the frequency of the nulled system f_n may be expressed as

$$f_n=\frac{c(P,T)}{2pL(P,T)}(n+\tfrac{1}{2}),$$

where $c(P,T)$ is the speed of sound in the sample material at P and T, n is the harmonic order number, p is the echo number, and $L(P,T)$ is the length of the sample at P and T. This null condition is a function of sample ambient temperature and pressure and the change of frequency required to maintain it is a direct measure of the changing sample environment.

The design objective for the automatic interferometer was the ability to track changes in the critical frequency to within a few parts in 10^7 over several hours. This requires not only a high enough feedback gain to minimize short term fluctuations but also very low dc drift to ensure that a stable baseline is maintained over the entire run. To a great degree these two requirements are conflicting as high gain requires high amplification and filtering which can introduce serious dc offsets in the signal processing chain. The method adopted to overcome this problem was first to ac amplify the relevant signal and then to convert it to dc using a synchronous detector. This approach is similar in principle to a chopper-stabilized amplifier which is useful with low frequency signals.

A comparison of the block diagram of the basic interferometer of Fig. 1 and that of the automated interferometer of Fig. 2 shows the changes made for automation. The oscillator has been replaced with a voltage controlled oscillator (VCO) and a double balanced mixer (DBM) has been added between the oscillator and the rf switch. The oscilloscope has been replaced with a circuit which determines the null condition and maintains it by automatically changing the frequency of the VCO, thereby forming a phase locked loop.

As was the case with the basic interferometer, the output of the oscillator (VCO) is a continuous wave which is gated into pulses by the rf switch. However, in the case of the

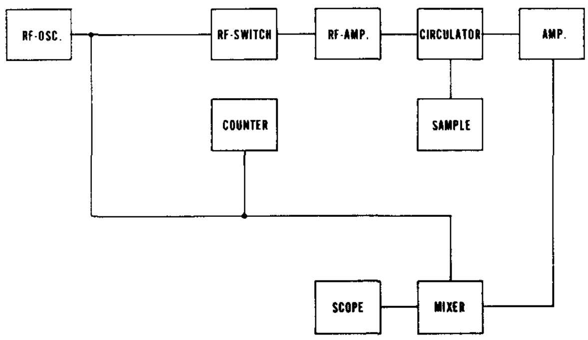

FIG. 1. Block diagram of the basic pulsed ultrasonic interferometer.

automated interferometer, the rf carrier within each pulse is 180° out of phase with that of the preceding pulse. The phase inversion is accomplished by the DBM configured to act as a phase inverter and is done to provide an ac signal in the detecting branch of the circuit. The necessary timing between the rf switch and the DBM is provided by logic signals A and B, respectively, shown in Fig. 3. The rf switch is on only when signal A is in logic state 1, while the output of the DBM is in phase with its input when signal B is in logic state 1 and 180° out of phase when signal B is in logic state 0.

As before, the signal is amplified, reflected in the sample, and phase detected in the mixer. And again for a given train of echoes, the output of the mixer is a series of dc pulses, but due to the phase inversion, the succeeding echo train will result in a signal which is the mirror image of the former reflected through the zero volts baseline as shown by signal E of Fig. 3. The result is an ac signal.

Next the signal is integrated. Logic signal C controls the integrator which is active only when the control signal is in logic state 1. The output is

$$\int_{t_1}^{t_2} V(t)dt,$$

where $V(t)$ is the input voltage and t_1 and t_2 are the turn on and turn off times, respectively. Times t_1 and t_2 are adjustable so that the signal from one particular echo can be selected. The amplitude of the output of the integrator then is proportional to the area under the $V(t)$ curve for the selected echo which renders successive signal processing steps less sensitive to signal pulse shape. The output of the integrator is shown as trace F of Fig. 3.

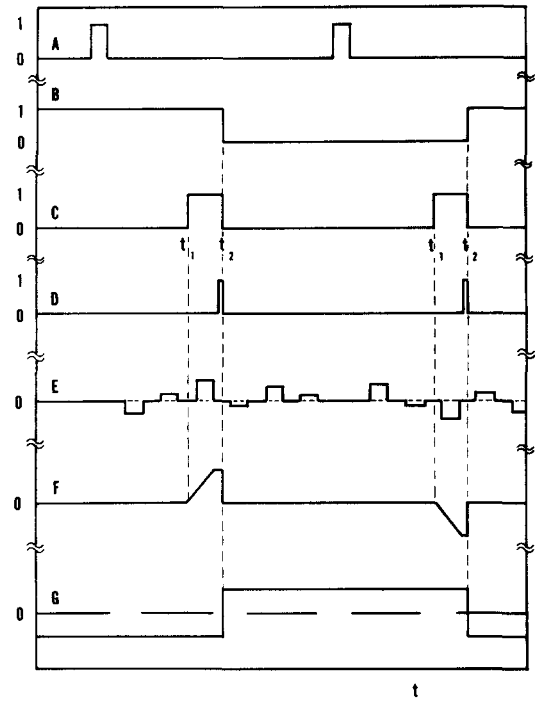

FIG. 3. Schematic diagram showing the relative timing between the controlling logic signals and output waveforms of the automated interferometer. The traces are identified as follows: A—logic signal to trigger the rf switch; B—logic signal to control phase inversion in the DBM; C—logic signal to activate the integrator; D—logic signal to activate S/H; E—output of the mixer; F—output of the integrator; and G—output of the S/H.

The sample and hold (S/H) following the integrator is triggered by logic signal D to sample the integrator output at the end of the integration period and to hold this value until the next cycle. The output of the S/H (trace G of Fig. 3) which is in phase with logic signal B, is amplified and then synchronously detected.

The synchronous detector simply consists of two switches (FET type) connected across the inputs of an operational amplifier which are alternately switched on and off by logic

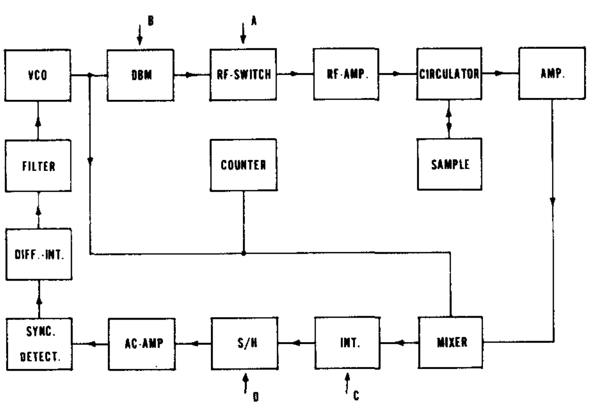

FIG. 2. Block diagram of the automated ultrasonic interferometer. The alphabetic symbols with the arrows indicate the insertion of controlling logic signals whose waveforms are shown in Fig. 3.

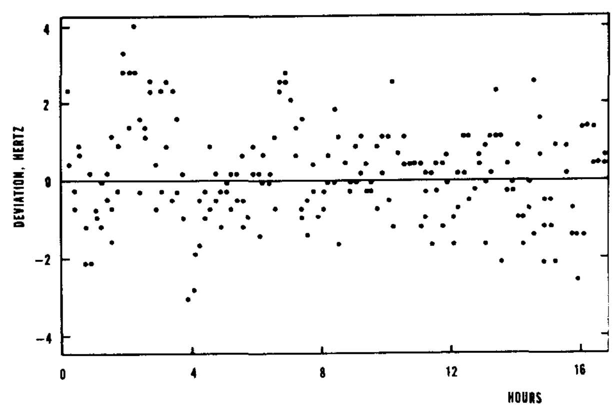

FIG. 4. Deviation of measured frequencies from least squares fitted curve with temperature as the independent variable plotted as a function of time. The standard deviation is 1.51 Hz with radio frequency of about 10 MHz.

signal B. The amplifier is configured as a differential integrator and its output controls the frequency of the VCO.

A fused quartz rod (75 mm long$\times$1.7 mm diam) was used as the sample for evaluation tests of the interferometer. The transducer was AC cut quartz, coaxially plated, had a fundamental frequency of 10 MHz, and was bonded to the rod using sodium salicylate. The sample was thermally lagged by a large water bath. Sample temperature was monitored using a digital quartz thermometer. The frequency was least squares fitted as a function of temperature using OMNITAB II. The deviations of the measured frequencies from the calculated curve are plotted in Fig. 4 for a typical 17-h run. The standard deviation for the data in Fig. 4 is 1.51 Hz.

[1] 1 Pa $= 10^{-5}$ bar.

[2] R. Truell, C. Elbaum, and B. B. Chick, *Ultrasonic Methods in Solid State Physics* (Academic, New York, 1969), Chap. 2.
[3] H. J. McSkimin and P. Andreatch, J. Acoust. Soc. Am. **34**, 609 (1962).